DOE/SC-ARM-0804

ARM Climate Research Facility Workshop Report

November 2008

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Contents

1. Introduction

The Atmospheric Radiation Measurement (ARM) Climate Research Facility (ACRF) workshop, held October 21-22, 2008, brought together approximately 30 climate research scientists to discuss the role of ACRF in solving outstanding climate science issues. The ACRF is composed of three fixed sites (the North Slope of Alaska, the Southern Great Plains, and the Tropical Western Pacific), two mobile sites, and aerial measurements. The mission of ACRF is to provide high-quality, long-term, continuous measurements needed to determine the effects of atmospheric water vapor, clouds and cloud properties, and aerosols on the radiation balance of the atmosphere across a range of climatic regimes. ACRF is a Department of Energy (DOE) national user facility that supports the broad climate research community. The ACRF includes support for short term field campaigns, but the emphasis of the program is on long-term observations.

The ACRF workshop opened with an overview of the program and a discussion of the workshop goals by Dr. Wanda Ferrell, the DOE Program Manager for the ACRF. The primary purpose of the meeting was to identify strategies for the use and structure of the ACRF to support future scientific investigations and to address remaining scientific uncertainties associated with climate processes. Workshop attendees were asked to consider several questions in a series of breakout sessions:

- What are the outstanding science questions for the next ten years?
- What specific locations are appropriate to address science questions?
- How long an observational period will be required at each location?
- What measurements, instruments, and data products are needed to address the science questions?

Participants were encouraged to provide creative input for site location and required measurements to best address each science question. This science-based feedback will provide useful input to ACRF as it considers whether the current ACRF configuration is optimum or needs to be adjusted as we look to address pressing issues over the next five to ten years. This self-evaluation by the ACRF is part of a larger strategic planning exercise being undertaken by the DOE Office of Biological and Environmental Research (BER) Climate Change Program.

In addition to the set of four questions, which provided the outline for the two-day meeting, participants were given some general guidelines for the use of ACRF which helped to constrain what activities should and should not be considered. As a national user facility, the ACRF provides operational and logistical support for campaigns using any of the ACRF resources and infrastructure. The ACRF does not provide support for research to analyze the data collected by the facility. That work is supported by ARM science and other research programs. And, while DOE continually invests in the maintenance and advancement of the ACRF, the ACRF does not purchase new instruments for a given campaign.

This report includes a description of the workshop proceedings, a summary of the topics discussed and of the high priority issues identified by the group. Additional meeting details are provided in a series of appendices, which include the meeting agenda and participants and notes on the meeting discussions that led to the final conclusions.

2. Logistics and Outcomes

The ACRF workshop was organized around a series of plenary and breakout sessions (see the workshop agenda in Appendix 1). The objective of these sessions was to identify a set of unanswered science questions that ACRF is well positioned to address and then to consider whether the current configuration of the ACRF was best suited to address these questions. For each question raised, workshop participants were asked to provide input on where the issue could be studied most effectively regardless of whether the location corresponded to an existing ACRF site.

Plenary sessions were used to give instructions to the group and collect information. Between plenary sessions, the group was divided into two parallel breakout sessions each with the same charge. The purpose in dividing the group was simply to facilitate discussion in smaller groups.

In the first breakout, the two groups generated lists of questions or issues. During this session, one group generated a list of 42 science questions while the other group took a different approach and identified a shorter list of 20 issues that were grouped in five categories: scale, aerosol impacts on clouds and precipitation, cloud dynamics, boundary forcing, and radiative effects. During a plenary session that followed, the two groups worked together to assemble a composite list of high priority items. In this exercise, eleven questions were identified (listed in Appendix 2). These questions became the focus for the remainder of the workshop.

In subsequent breakout sessions, the groups worked to identify the optimum location to address each science question, the amount of time needed at that location, and the measurements and data products needed. Not all questions were discussed equally. Plenary sessions were used primarily to share results between the two groups. In the final plenary session, the group recommended five main focus themes that had come out of the workshop. These are the items that were viewed as being most important to pursue. The five target issues were:

1. Focus on the diurnal cycle, a time scale that ACRF is uniquely qualified to address.
2. Improve measurements of cloud properties and enable measurements during precipitation.
3. Determine the impact of aerosols on cloud properties.
4. Obtain measurements of trade cumulus, a key cloud type for climate processes
5. Increase emphasis on surface process measurements.

These target issues and a summary of the discussion topics that led to promoting these topics are discussed further below. Two of the target issues: “aerosol measurements at an elevated site” and “measurements of trade cumulus” would require observations in a new location. The remaining three could be carried out at the existing ACRF locales. In general, for the science issues put forward at the workshop, the majority could be addressed at the existing sites. Along with the five target science issues, this understanding that the existing sites provide the means to address many outstanding science issues was an important outcome of the workshop.

3. Target Issues

1. Focus on the diurnal cycle, a time scale that ACRF is uniquely qualified to address

The diurnal cycle is an important mode of variability in the climate system. While the diurnal variation of solar input at a given location is relatively simple, nearly every component of the climate system responds to this forcing, which makes the analysis of the diurnal cycle a difficult yet important problem. In response to daily solar forcing, precipitation cloudiness, boundary layer structure, temperature, wind fields all vary with interactions between the various parameters. Climate models include the solar forcing but generally have a difficult time capturing the correct magnitude and timing of the response in the various parameters. ACRF is well positioned to address this issue because of the ACRF fixed locations and high temporal sampling rate. Many satellite programs are unable to capture this cycle either because they operate in sun synchronous orbits or because of long scene revisit intervals. This capability is mentioned here in part because it permeates each of the key science issues identified at the workshop and because in several cases, ACRF's sampling strategy should be improved to better address diurnal cycle issues. Potential improvements include better temporal sampling of upper tropospheric water vapor, measurement of nighttime aerosol (e.g., with star photometry), and nighttime sky imaging (using an IR imager). This work would be applicable at any of the current ACRF fixed or mobile sites.

2. Improve measurements of cloud properties and significantly improve ability to measure cloud properties during precipitation

ACRF is focused on the interactions of clouds with solar and terrestrial radiation. A critical part of this work is measuring microphysical properties (cloud ice and liquid water content, cloud particle sizes, shapes, and distribution). ACRF measurements and research have long included an emphasis on obtaining the best possible microphysical parameters with the available instrumentation. This research is reaching the point where additional reduction in uncertainties in these critical parameters requires new instrumentation for applications such as specifying radiative heating profiles, measuring vertical velocities, and studying the convective triggering and evolution of 3D cloud fields. The ACRF already operates a subset of the necessary instrumentation to make some progress on these problems—each of the ACRF sites include a cloud radar, (operating at 35 or 94 GHz), a cloud lidar, and balloon-borne temperature and humidity sensors. However, these measurements are inadequate for determining detailed microphysical properties in most cases. Additional instrumentation needed to improve retrievals of microphysical processes includes radars at two additional frequencies for a total of three at a single site (35 GHz, 94 GHz, plus a precipitation radar) and a Doppler lidar. Evolving to a multi-frequency scanning radar is a medium-term goal to bridge our understanding of two-dimensional (2D) retrievals to the three-dimensional (3D) cloud field. In order to resolve the diurnal cycle a Raman or differential absorption lidar (DIAL) is required to measure water vapor profiles with high temporal resolution. Currently a Raman lidar is available only at the Southern Great Plains site. These additional microphysical measurements would allow detailed cloud properties to be derived even in the presence of light precipitation. It is important to couple these detailed measurements of cloud microphysics to vertical motion on the cloud scale to couple microphysics with meteorological processes. Vertically pointing Doppler radars provide the vertical motion of cloud particles but, to separate particle motion from air motion, a wind profiler is required. This work could be carried out at any of the current fixed ACRF sites.

3. Determine the impact of aerosols on cloud properties

The radiative impact of aerosols on clouds has been identified by the most recent IPCC report (AR4) as the largest source of uncertainty in radiative forcing of climate. However, the effects of aerosols on clouds are very difficult to quantify, in part, because it is often difficult to separate aerosol effects on clouds from meteorological effects. Doing so requires observing many clouds from similar meteorological regimes with varying aerosol amounts, which generally takes a long time. Aerosol effects on clouds also depend upon the detailed composition of the aerosol. Measuring aerosol composition generally requires in situ measurements that can be obtained only from the ground or from an aircraft (not remotely with a radar or lidar). Under some circumstances, aerosol properties are well mixed in the boundary layer and surface measurements are indicative of those at cloud level. For higher altitude cloud layers or when the cloud layer is decoupled from the surface, the properties of aerosol at the cloud altitude may be different than the properties near the ground. When possible, therefore, it is very useful to measure aerosol properties at, and immediately below, cloud level. Obtaining many samples from an aircraft is expensive. One possible solution to this problem is to identify a site that includes a significant elevation change over a relatively short distance. At such a site, typical ACRF cloud remote sensing instruments could be placed at the lower altitude site, while in situ aerosol instruments could be placed at the higher elevation, one at which clouds are frequently observed. With this observation configuration, it would be possible to obtain a long time series of aerosol properties aloft in conjunction with cloud properties. Limited data were collected during the ARM Mobile Facility (AMF) deployment to Germany that could address this problem, and the upcoming AMF deployment to Storm Peak in 2010/2011 may also prove useful. *Ultimately, a site would likely need to be chosen that is optimized for studying this issue, one with a broad range of aerosol properties and a minimum influence expected from orographic effects.*

4. Obtain measurements of trade cumulus, a key cloud type for climate processes

Trade wind cumuli cover a large portion of the Earth's oceans, particularly in sub-tropical regions. These clouds have been identified as particularly problematic in climate change scenarios. Relatively small changes in fractional coverage of these fair weather clouds has a large impact on the solar radiation reaching the surface and, therefore, on ocean temperature. Consequently, these clouds are responsible for a large portion of the spread in climate model predictions of surface air temperature. Key measurements for addressing this problem include a radar (for cloud properties) and a Raman lidar (for detailed measurements of water vapor over the diurnal cycle). The radar should scan at least in a plane (if not in 3 dimensions) to get a good measurement of spatial cloud cover and provide high temporal resolution. It would be possible to measure marine boundary-layer cumulus similar to the ones suggested here at the Manus site or during the upcoming AMF deployment to the Azores. However, these sites do exhibit significant differences (in terms of temperature and humidity profiles, and possibly cloud characteristics) from the sub-tropical regions where trade cumulus are most prominent. *Therefore, it would be ideal to locate a site in a subtropical region away from significant orographic effects. Possible solutions to the siting problem include deploying the AMF on a cargo container ship or on an oceanographic research vessel.*

5. Increase emphasis on surface process measurements

ACRF has generally focused on direct measurements of the clouds, aerosols, and radiation that comprise its mission targets. However, other parameters have important influences on these parameters. An important set of such parameters are those that control energy fluxes at the Earth's surface. By influencing the surface energy balance, these parameters impact surface heating, vertical air motion, transport of aerosols, and cloud development. Correctly defining the properties of the lower boundary is very important for constraining model simulations of a region because of these effects. Important surface properties that impact the energy budget include the spectral albedo (solar surface reflectance), vegetation cover, subsurface moisture, and the measurement of the surface heat fluxes themselves. Most of these measurements are currently being taken at the Southern Great Plains site only and the performance of the measurements in terms of uncertainty of and spatial averages may not meet the current needs of the modeling community. Improvements to these measurements, with an increased focus on characterizing their output, are important to better constrain the lower boundary of the atmosphere. To better relate surface process measurements to climate change research, these measurements also should be added to our other ACRF research sites. It is anticipated that such boundary condition data will be important for the success of future integrated Earth system models (e.g., for the coupling of atmospheric system components with vegetation and subsurface hydrologic system components).

4. Summary of Topics Discussed

The list of science questions developed during the first breakout and subsequent plenary sessions generated a great deal of discussion about possible applications of ACRF data. In this section, a summary is given of the main discussion topics.

What are the spatial and temporal scales appropriate for ACRF data?

The ARM Climate Research Facility is comprised of continuously sampling ground-based sites and airborne support to augment the observations for these sites. Data are collected at these sites with high temporal resolution. The high temporal resolution of these data make ACRF observations ideal for studying the diurnal cycle, an important mode of climate variability that is not well sampled by most satellite sensors. Meanwhile, because of the discrete nature of surface sites, ACRF is best suited to study processes at the local or cloud scale. This combination of spatial and temporal scales makes ACRF observations uniquely suited for studying local cloud processes, many aspects of which remain among the most poorly represented processes in climate models.

How can we better measure the microphysical properties of clouds and how do these properties relate to vertical velocity?

One of the primary missions of ACRF is to provide measurements of cloud properties and radiative fluxes to improve the representation of cloud processes in climate prediction models. A number of advances have been made in the use of remote sensing instruments to measure cloud properties; however, the current measurement strategy could be improved to more accurately measure cloud properties and account for the effect of precipitation by expanding the suite of cloud property measurements. It also was felt that the emerging work on measuring vertical velocities is extremely important. Coupling these measurements with cloud properties provides details on cloud processes, which can then lead to insights for developing cloud parameterizations in climate models.

What are the time-averaged profiles of radiative and latent heating?

Vertical profiles of cloud properties combined with profiles of temperature, humidity, and aerosol can be used to calculate vertical profiles of radiative heating. Improved measurements of cloud properties would improve the quality of these derived heating profiles. Providing a high temporal resolution source of water vapor profiles, such as from a Raman lidar, also would be a great addition to radiosondes, which are launched only a few times per day. Traditionally ACRF has not devoted as much attention to precipitation or latent heating as it has to radiative processes. The best tool for measuring latent heating profiles would be a precipitation radar. Adding a precipitation radar to the suite of ACRF instruments would provide the means to measure the total diabatic heating (radiative plus latent) and would also facilitate the observation of cloud properties in the presence of precipitation.

How do we account for 3D radiative transfer in climate modeling and remote sensing measurements?

There are outstanding questions regarding the degree to which 3D effects of clouds impact radiative heating profiles and the measurement of cloud properties. Studies attempting to resolve these questions generally must deal with inhomogeneities in surface properties, which can introduce complicating variability in radiative fluxes. It was proposed that, to definitively address questions about the importance of 3D radiative clouds effects, a study should be carried out with measurements in a region where surface inhomogeneities are minimized. Possible study regions suggested included a snow-covered surface, a boreal forest, or a suitable maritime site. A key instrument for such a study would be a scanning cloud radar.

What are the effects of aerosols on climate including impacts on liquid and ice clouds?

Much uncertainty exists concerning the impact of aerosols on climate. To reduce this uncertainty, measurements of vertical profiles of aerosol absorption are needed to determine profiles of radiative heating due to aerosols, and coincident measurements of aerosols and cloud properties are needed to determine the effects of aerosols on cloud processes. A lot of the discussion concerning the impact of aerosols on clouds had to do with choosing the appropriate location. Other factors, such as orography, can have a large impact on cloud effects. It is also important to stratify aerosol/cloud measurements by meteorological regime. These complicating factors suggest that quantifying aerosol impacts on clouds may require more effort/duration than other processes.

What are the characteristics of upper tropospheric humidity?

Quantifying the distribution of upper tropospheric humidity is important for determining profiles of radiative heating and for understanding the life cycle of cirrus clouds. Measurements of upper tropospheric humidity are very difficult. In situ measurements from radiosondes provide very good vertical resolution, but typical humidity sensors have difficulties with the very low water vapor amounts found at high altitudes. Remote sensing techniques can provide high temporal resolution observations but typically do not work during the day or in the presence of low clouds. A strategy should be developed to take best advantage of available technology to optimize this measurement.

What is the role of orography in cloud and precipitation processes?

In many parts of the world, patterns of precipitation are driven to a large extent by orography. But climate models do a very poor job of capturing these effects. Often the models do not resolve significant orographic features. It would be very beneficial to obtain measurements of cloud and precipitation formation processes in a region dominated by orographic forcing such as the Colorado front range. Careful thought would have to be given to siting because of the spatial inhomogeneities inherent in orographically forced systems.

What is the role of surface processes and properties in cloud formation?

Surface properties (albedo, land cover, subsurface moisture) and related processes, including those tied to the diurnal cycle, have an important influence on cloud formation. Surface heat flux measurements provide an important constraint on model simulations over the ACRF sites. Measurements of surface properties and surface fluxes are made at the Southern Great Plains but there are questions concerning the quality and application of these measurements. It was proposed that a value added product (VAP) could be developed that would help users properly apply the range of measurements available. Much less information exists on surface properties available at the other ACRF sites. There was interest in exploring the addition of surface property measurements at the other sites.

What are the characteristics of trade cumuli?

Trade cumuli are a very widespread cloud type and one with a particular sensitivity to climate change. It would be valuable to obtain measurements of these clouds in a maritime environment to fully describe their properties and the relationship between cloud properties and vertical motion. It is expected that a relatively short period of time, perhaps a year to a few years, would be sufficient to observe the range of characteristics exhibited by these clouds. Ideally such an experiment would be held in a maritime location in the subtropics. Trade cumuli could be observed at other locations including existing ACRF sites and the upcoming AMF deployment to the Azores; however, the boundary layer conditions would be different than found in the trade latitudes, which could have an impact on cloud properties.

Appendix A:

ACRF Workshop Agenda
Oct 21-22, 2008

HYATT REGENCY RESTON
1800 Presidents Street, Reston, Virginia 20190
Phone: 703 925 8120 Fax: 703 925 8144 • reston.hyatt.com
Main meeting room - Lake Anne
Breakout room - Lake Thoreau

Tuesday Oct 21

8:30	Plenary – Welcome, introductory comments, instructions
9:15	Breakout (2 groups) – Identify and discuss important unresolved science questions that could be addressed with the ACRF
10:45	Break
11:00	Plenary – Merge conclusions from two groups; presentations by moderators and discussion; instructions for afternoon breakout
12:00	Break
1:00	Breakout (2 groups) – Discuss locations (as specific as possible) appropriate to address science questions identified in morning session; discuss deployment duration required to address each question.
2:30	Plenary – Merge conclusions from two groups; instructions for next breakout
3:30	Break
3:45	Breakout (2 groups) – Begin discussion of measurements, instruments, and data products needed to address science questions.
4:45	Plenary – Short discussion of afternoon findings; plans for next day
5:30	Adjourn for the day

Wednesday Oct 22

8:30	Plenary - Discussion and instructions
9:15	Breakout (2 groups) – Continue discussion of measurements, instruments and data products
10:45	Break
11:00	Plenary – Merge conclusions from groups; instructions for the afternoon
12:00	Break
1:00	Breakout (2 groups) – Timeline for addressing science questions
2:30	Plenary
3:30	Adjourn

Appendix B:

Attendees

Workshop Participants
Thomas Ackerman, University of Washington
Mark Boslough, SNL
Larry Carey, University of Alabama Huntsville
Manvendra Dubey, LANL
Ann Fridlind NASA, GISS
Steve Ghan, PNNL
Anthony Janetos, PNNL
Rich Ferrare, NASA Langley
Jean-Christophe Golaz, GFDL
Jim Hack, ORNL
Everette Joseph, Howard University
Rao Kotamarthi, ANL

Henry Loescher, NEON Inc.
Gerald Mace, University of Utah
Greg Mcfarquhar, University of Illinois
Mark Miller, Rutgers University
Dave Randall, Colorado State University
Courtney Schumacher, Texas A&M
Peter Thorne, Met Office Hadley Centre
Margaret Torn, LBNL
David Turner, University of Wisconsin
Taneil Uttal, NOAA
Sandra Yuter, North Carolina State University
Warren Wiscombe, BNL

Moderators
Robert Ellingson, Florida State University
Steve Klein, LLNL

Rapporteurs
James Mather, PNNL
Raymond McCord, ORNL
Beat Schmid, PNNL
Doug Sisterson, ANL
Jimmy Voyles, PNNL

DOE Observers
Kiran Alapaty
Todd Anderson
Wanda Ferrell
Michael Kuperberg
David Lesmes
Anna Palmisano
Rick Petty
David Thomassen
Robert Vallario
Ashley Williamson

Appendix C:

Science Questions from Second Plenary Session

1. How do aerosols influence ice-containing clouds?
2. How do aerosols influence liquid water clouds?
3. What is the relationship between aerosols and precipitation?
4. What controls the distribution of vertical velocity and how does it vary at spatial scales?
5. What is the relationship between dynamics and cloud properties?
6. How does precipitation evolve in clouds?
7. What is the role of orography in cloud formation and precipitation?
8. What is the role of surface processes and properties in cloud formation (albedo, diurnal cycle, subsurface moisture, land cover)?
9. What is the profile of time-averaged radiative and latent heating and cloud properties?
10. How do we account for 3D radiative transfer in climate modeling and remote sensing?
11. What characterizes and controls the upper tropospheric humidity?

Appendix D:

Discussion Notes from Breakout Sessions

Once the short list of eleven science questions/issues were identified, these issues focused the discussion in subsequent breakout and plenary sessions although additional important topics were raised. The following sections reflect the issues raised by the groups, which ultimately led to the identification of the five target issues.

Matching the spatial and temporal scale of science issues to those observable from ACRF sites

One of the primary missions of ACRF is to improve the representation of clouds and radiation in climate models. ARM science has done a good job at identifying where certain parameterizations have problems yet hasn't done as good a job in providing solutions. As we consider what science questions and issues ACRF should address looking forward, we should consider what science questions we can ask given the scale of observations available with ACRF instruments. For example, while the Manus and Nauru sites in the Tropical Western Pacific are affected very differently by El Nino/Southern Oscillation (ENSO), it is probably not realistic for these two sites to provide significant insight into ENSO because of the large spatial scales and long temporal scales involved. Study of the Madden-Julian Oscillation (MJO) poses similar problems in terms of spatial scale, but the problem may be more tractable because the modeling problems related to the MJO have more to do with physical processes that are observable by a point site and the temporal scale is much shorter.

If we need to observe a phenomenon over a broad range of spatial scales to make progress in understanding it, then ACRF is probably not well suited to addressing that problem. However, ACRF is well positioned to support process studies at the cloud resolving model scale. ACRF can impact cloud resolving models (CRMs), which can then be scaled up to GCMs. We should not ignore the larger scale; it simply shouldn't be our main focus.

In terms of temporal scale, ACRF is ideally suited to address short time scales including the diurnal cycle. This is an area where ACRF, with its high data collection rate, can really contribute. Many satellite observing systems operate in a sun synchronous orbit or have relatively long revisit periods making them ill-suited to observing the diurnal cycle.

Improved measurements of microphysical parameters and the relationship of cloud properties to cloud-scale vertical motion

Vertical motion is intimately linked to clouds. Upward motion forces cloud formation while downward motion results in cloud dissipation. Therefore, to better understand cloud processes we need to know the evolving distribution of vertical motion coincident with observations of clouds and aerosol. ACRF has done a good job with some cloud processes but needs to focus on the connection between dynamics and clouds. We are currently not in a position to do this. ACRF has made significant advances in measuring cloud microphysical processes but is approaching a limit given the instrument suite currently available at the ACRF sites. A variety of aerosol products have been developed, but additional aerosol measurements are also likely to be required. ACRF has not done a good job of measuring vertical velocity, although a recently formed focus group has begun examining what can be done to improve the observation of this parameter.

Vertical Velocity

Vertical velocity measurements are needed for many types of process studies. If we can measure the turbulent spectrum, that is a good step toward describing cloud processes. With the collection of Doppler spectra from the cloud radars and increased attention to Doppler moments from the wind profilers, we are developing realistic methods for observing vertical motion in clouds. This emerging capability is motivation for turning our attention to this problem. There is a question of spatial scale. Vertical motions on a range of scales are important for cloud evolution but, given the scale of ACRF measurements, it is most reasonable to focus on cloud-scale motions.

The vertical velocity focus group is working on distributions of vertical velocities in clouds. One goal of this group is to obtain a mass flux. This is a quantity that is parameterized by cloud models. Like other validation work, a careful matching of scales is required. Mass flux in a model is not a point measurement. It represents some particular scale, so appropriate averaging is needed with the measurements.

It is also important to relate the distribution of vertical velocity to microphysical parameters. Calculating covariances of vertical velocity with water content data would be very useful for diagnosing cloud evolution processes.

It is not clear whether the accuracy of radar retrievals of vertical velocity is adequate for these applications. The requirement by the modeling community is on the order of 10 cm/s, but current techniques are expected to provide uncertainties on the order of 50 cm/s. There is a need to evaluate the adequacy of current vertical velocity retrievals for these and related applications.

Cloud microphysics

Cloud microphysical properties are of central importance to ACRF. Detailed information about cloud microphysics is necessary for describing the evolution of cloud fields and the interaction of radiation with cloud fields. A variety of retrieval techniques have been developed to obtain microphysical cloud products. The most promising involve combinations of instruments including cloud radar, lidar, and radiometer. However, with current ACRF instrumentation, even the most sophisticated retrievals cannot accurately retrieve key parameters for many cloud types. The basic parameters to measure are water content, number concentration, and particle size. In a radar-based retrieval, there are three independent pieces of information (reflectivity, Doppler velocity, and Doppler spectral width) so, in some cases, a unique retrieval of the basic cloud properties is possible. However, many clouds have bi-modal particle size spectra, so six pieces of information are required. Retrieving the characteristics of both modes requires at least two radar frequencies.

Because of the basic limitations on available information from current instrumentation, the most promising avenue for obtaining accurate cloud property information is to put together a multi-wavelength system to constrain the problem as much as can be reasonably done. A proposal for such a system includes a three-wavelength radar, a Doppler lidar, a microwave radiometer, and a window region infrared radiometer. The three radar wavelengths should include the two typical cloud radar frequencies, 35 and 94 GHz, and a frequency used for precipitation measurements in the range of ~1-13 GHz. At a minimum, Doppler moments should be collected at each radar frequency though full Doppler spectra would likely prove to be very useful. The radiometers provide a constraint on column water path. The lidar would provide vertical velocity but weighted by the second moment of the size distribution and would therefore be helpful in separating cloud from precipitation. It would be useful only, however, in low optical depth clouds or below clouds where it also would provide information about aerosols. It also may be possible to observe processes associated with nucleation near cloud base, even in optically thick clouds.

There are many details that would have to be worked out in the deployment of this system such as whether one or more of the radars should be scanned. Such a system would be quite expensive with a price tag of at least $2M-$3M. In addition, there would need to be a commitment to develop appropriate data products for the retrieval of cloud properties. The raw data would not be useful to the general science community. But such a system would have the potential to accurately measure parameters needed to address a range of science questions.

Most likely, at least two of the radar systems should be vertically pointing only to obtain Doppler velocity measurements. To scale the results from the vertical profile, one radar could be scanned along with one or more radiometers. In addition, coupling the observations with a cloud resolving model could be used to scale up to the cloud scale.

What is the profile of time-averaged radiative and latent heating and cloud properties?

Our ability to say anything about radiative heating is on the edge of being useful on less than hourly time scales. The thing that is holding this up is our ability to measure cloud microphysical properties. If we want to improve our error bars, we need to go to a multiple wavelength system. If we want to go to a diurnal cycle, we need to obtain the horizontal cloud fraction at a high temporal resolution, which means going to a scanning radar for at least one wavelength.

Measuring radiative heating over the diurnal cycle also requires measuring profiles of water vapor with high temporal resolution. Passive techniques using infrared or microwave spectroscopy can provide profile information in the boundary layer but, to get water vapor in the mid and upper troposphere, a Raman or DIAL lidar is necessary. For aerosol profiles, a Raman or High Spectral Resolution lidar (HSRL) is necessary to minimize the number of assumptions needed to obtain extinction.

There are two main techniques that have been used to measure latent heating: with a radiosonde budget analysis or with a scanning precipitation radar. With a precipitation radar, heating is derived from gradients in the precipitation profile, but there are uncertainties. Typically the horizontal transport of clouds is not accounted for, so you would have to decide on the scale. In the Tropical Warm Pool-International Cloud Experiment (TWP-ICE) and related experiments, the tendency has been to go for the budget over a scale of ~100 km. However, to test cloud resolving models, it would be desirable to get to a smaller scale. One would want to get to a resolution of ~100 m, which is roughly the scale of a radar range cell and therefore hard to achieve. To advance the understanding of latent heat with respect to cloud properties in cloud resolving models, it is important to obtain a measurement resolution on the order of ~100m.

How do we account for 3D radiative transfer in climate modeling and remote sensing?

There are several reasons why it would be desirable to study 3D radiative transfer effects:

- to know if these effects need to be parameterized in climate models
- to know if 3D cloud effects impact satellite and/or ground based retrievals.

To study 3D atmospheric effects, it is important to avoid inhomogeneities in the surface, which also can introduce inhomogeneities in the radiance field. This is a problem at the ACRF sites. All of the major ACRF facilities except for the SGP are coastal sites and the SGP site is a patchwork of cropland and pasture. Nauru would probably be the best tropical site except there is an island-generated cumulus effect when the wind is easterly. One possibility would be the SGP site in winter when the snow-cover would homogenize the surface albedo.

It would be desirable to do this study over a uniform surface like a boreal forest or at sea. At a good site, you could observe a range of conditions and decide if 3D effects could (and should) be included in a GCM parameterization.

The key measurement for 3D radiative transfer is a scanning radar to provide the 3D cloud field. Such a radar could be scanned over a volume or in a plane. The latter would be an improvement over the 1D view and would allow a much shorter cycle time than a full 3D scan. It also would be useful to boresight radiometers (microwave and IR) on the radar scanner to supplement the radar reflectivity. Another potential source of 3D cloud information is microwave tomography. For ground validation, it should be sufficient to use the existing flux measurements available at the ACRF sites.

What are the impacts of aerosols on climate?

Aerosol direct and semi-direct effects

It is noted that aerosol forcing is the most uncertain of all climate forcings. Aerosol forcing can be grouped into direct, semi-direct, and indirect effects. To improve the characterization of direct and semi-direct effects, it is necessary to obtain vertical profiles of aerosol absorption. Established in situ techniques exist for measuring aerosol absorption and extinction but obtaining profiles requires mounting sensors on aircraft, which cannot be done on a continuous basis. There are techniques to measure profiles of extinction and absorption that make use of lidars. The micropulse lidar, which is operated at all ACRF sites, can be used to measure profiles of aerosol extinction when combined with measurements of aerosol optical depth. Aerosol optical depth is available during the day with passive radiometers. Measuring aerosol optical depth at night would require the addition of a starphotometer. The combination of aerosol optical depth with lidar measurements to obtain extinction profiles can be a labor intensive process; however, NASA's MPL-Net program has been focusing on this problem and has developed an automated procedure. It would be particularly interesting to obtain extinction profiles for the AMF deployment to

Niamey, Niger. Measuring profiles of aerosol absorption is more difficult and would require the addition of a lidar that uses multiple wavelengths and dual-polarization. Such a lidar would yield measurements of size, refractive index, and single scatter albedo. This could be feasible in five to ten years but would require a significant investment.

First and second indirect effects

Aerosol effects on ice containing clouds are of high importance. Improved understanding of these effects requires a combination of laboratory studies, high mountain experiments, and aircraft studies of ice-nuclei. A key instrument for this work is a Continuous-flow Diffusion Chamber in conjunction with a Counterflow Virtual Impactor. This instrument separates cloud particles from interstitial aerosol making it possible to isolate the aerosol particles contained in ice crystals. It also would be important to measure aerosol composition (for example, using an Aerosol Mass Spectrometer). The ACRF North Slope of Alaska (NSA) site is a good place to study Arctic stratus containing ice. Tethered balloons, kites, or Unmanned Aerial Vehicles are possible alternatives in this region to conventional airborne platforms.

Aerosol effects on water clouds are very important as well. There are important questions regarding which aerosols nucleate cloud drops. Cloud Condensation Nuclei measurements are important for this work as are measurements of composition and size distributions (for example with an Aerosol Mass Spectrometer and an Aerosol Particle Spectrometer). Marine stratus is a good environment to study the aerosol effects on water clouds. The AMF deployment to the Azores will provide a good opportunity for this work. For deployments such as the Convective and Orographically Induced Precipitation Study (COPS; the AMF deployment to the Black Forest in Germany) orographic effects make it difficult to isolate the effects of aerosols.

To evaluate the aerosol impacts on clouds, data need to be stratified by meteorological conditions. In this way, aerosol effects can be separated from dynamic effects. For this analysis, a sufficient number of cases are needed. This suggests a need for long-term observations – probably on the order of years. The AMF will be in the Azores for almost two years. Given that the time scale of a synoptic system is on the order of ten days, we will sample approximately fifty weather systems over the course of the deployment. How will we know when we have enough data? We don't a priori. This will depend in part on how much variety there is among the cloud systems. We need to collect enough observations to get out of the "noise" in the characteristics of a particular type of cloud system (cloud/meteorological setting).

Apart from the absence of orographic effects, another advantage of marine observations is the synergy they provide with satellite measurements which tend to do better over water (don't have as variable a surface over water). A difficulty with this environment is that clouds over water exhibit a narrow range of vertical velocities, which in turn limits the variability of cloud properties.

Although a site in the vicinity of mountains is problematic because of orographic effects on clouds, it does present an opportunity as well. In a mountainous region, a site could be placed at a high altitude, within the cloud layer, providing a means of sampling cloud properties from the ground. Meanwhile, nearby sites at lower altitude cloud provide measurements of cloud properties below the cloud. This measurement configuration would provide the means of obtaining long-term measurements of in situ cloud measurements in conjunction with below-cloud aerosol measurements. The upcoming deployment of the second AMF to Storm Peak, Colorado, will provide a prototype for this type of experiment.

Feingold et al. have shown that, in areas with strong topographic forcing, dynamics rules over topography. It remains to be seen whether the long-term benefits of this sort of experiment will prevail over the complications of orography (which has already been observed during the AMF deployments to Pt. Reyes, California and Germany), but the Storm Peak deployment will provide a test of this concept.

A similar experiment could be done with aircraft. There would be less observation time but one would not have to deal with the orographic effects. It would be important to include a measurement of liquid water path that could be done with a G-band microwave radiometer. For such an experiment, it would be important to adopt a routine sampling strategy such as those that are being planned for the Routine Clouds with Low Optical Water Depths (CLOWD) Optical Radiative Observations (RACORO) and the Small Particles in Cirrus (SPARTICUS) campaigns. We would need to be careful about limiting the aircraft instrument payload because an excessive number of instruments would limit the available time for routine measurements.

Other aerosol-issues

Other aerosol topics discussed included the effect of aerosol on snow albedo, study of areas with high aerosol loading, and experiments using controlled releases of aerosols. To study the effect of snow albedo, it was recommended that coincident measurements be made of surface albedo and snow properties. There was some debate about the need to study areas of high aerosol loading. Areas of large fires (California) could present a target of opportunity. Complete processing of Pt. Reyes and COPS data sets (AMF) are needed so we can understand these cases. However, we also need in situ data sets (at cloud base).

Several additional sites (in addition to current fixed and AMF sites) for aerosol-indirect-effect studies were suggested:

- Beltsville, MD
- Korea
- Macehead, Ireland
- Jungfraujoch, Switzerland
- Gondola equipment at a ski resort such as Steamboat Springs, CO.

Suggestions for sites for studies of precipitation were:

- Chilbolton, UK
- Darwin, Australia.

Given the difficulties in separating aerosol effects from dynamical effects, one possibility for simplifying the study of aerosol effects would be through the controlled release of aerosol. In this way, an aircraft flight pattern could be carefully planned to sample cloud properties in the presence of a wide range of aerosol concentrations. For such an experiment, a large amount of material might need to be released. Such an experiment could provide some information about the potential viability of proposed geo-engineering techniques for mitigating climate change. An alternate strategy could be to measure cloud properties in the vicinity of ship tracks. The aerosol from ship tracks would not be as easy to work with because they tend to be very heterogeneous. A controlled release would be preferable. In the tropics, a so-called chemical equator has been observed (e.g., during TWP-ICE) that separates the relatively polluted air of the northern hemisphere from the much cleaner air in the southern hemisphere. The transition from polluted to clean conditions has been observed to occur over a very short distance providing another possible mechanism to study cloud properties under a wide range of aerosol conditions.

What characterizes and controls the upper tropospheric humidity?

Accurate measurements of upper tropospheric humidity are important for calculations of radiative heating and for studying cirrus processes. With a single point measurement at an ACRF site, it was noted that one can't really get at the issue of what is controlling upper tropospheric humidity. That requires information about convective outflow and related dynamics; but we can work on characterizing humidity. The available tools for measuring humidity are radisondes and Raman lidar (or DIAL lidar). Currently there is only one Raman lidar in the ACRF, at the SGP site. The current operational radiosonde used by ACRF, the Vaisala RS-92 suffers from a significant daytime dry bias due to solar heating of the sensor. Furthermore, the typical frequency of radiosonde launches at the TWP and NSA sites is twice/day. Water vapor profiles can change rapidly so this frequency may is inadequate for some applications. The Raman lidar can provide better time resolution but it is not available in the upper troposphere during daylight hours or when there are optically thick clouds in the lower troposphere. So upper tropospheric water vapor measurements present considerable challenges.

These problems are most severe in the tropics where water vapor concentrations are very low and solar interference is at a maximum. This is also where one would most want to make these measurements. One way to do better with the measurements is to go to a high altitude site, which would minimize interference by clouds, and simplify passive techniques. Possible high altitude sites include Mauna Loa, Mount Kilimanjaro, or the highlands of Papua New Guinea.

What is the role of orography in cloud formation and precipitation?

The impact of topography and rainfall are ignored in climate models; as models come down in spatial resolution, complex terrain will have to be addressed. Orographic forcing is not limited to the timing, location, and propagation of precipitation, but also to the snowfall line that changes with elevation, surface heating rates on the sunny side of the mountain versus the shady side of the mountain, mountain valley flow, etc. To a large extent, the cloud and precipitation patterns at the SGP (albeit far from the Rockies) would be totally different without the influence of the Rockies.

As climate models approach finer grid scales, convection will be forced to connect to the boundary layer and surface layer to resolve the diurnal cycle and convection, which are driven by surface and boundary layer conditions. Currently, models do a poor job of connecting convection to the boundary layer and none of the models do a decent job of connecting convection to boundary layer and surface layer fluxes. A site on the east slope of the Rockies in the United States (in the lower 48 states) was suggested. The proposed location of the AMF2 at Storm Peak in Steamboat Springs, Colorado, would be a suitable location and serves aerosol interests, as well.

The COPS field campaign in the Black Forest of Germany was designed to address the effect of topography on precipitation. Because of major international involvement, the COPS field campaign was extensively instrumented and should be of particular value to the role of orography in cloud formation and precipitation. Although there was much discussion about orographic forcing early in the workshop, the role of orographic effects in clouds and precipitation did not make it to the final high-level issues at the end of the workshop.

Mountains (North America): the impact of topography and rainfall are ignored in models. ACRF could address this with a site in complex terrain (like the front range of the Rockies).

What is the role of surface processes and properties in cloud formation (albedo, diurnal cycle, subsurface moisture, land cover)?

As climate models approach finer grid scales, convection will need to be connected to the boundary layer and surface layer in order to resolve the diurnal cycle and convection, which are driven by surface and boundary layer conditions. Currently, models do a poor job of connecting convection to the boundary layer and none of the models do an adequate job of connecting convection to boundary layer and surface layer fluxes. We need enhanced emphasis on measurements of surface processes at all of the current sites, not just at the SGP.

Critical parameters that affect surface properties include not only the surface fluxes, but land use, vegetation cover, soil moisture and subsurface moisture, and surface albedo. Correctly defining the properties of the lower boundary is very important for constraining model simulations. While most of these measurements are currently being done at the Southern Great Plains site, the resolution and spatial scale of the measurements, even at the Southern Great Plains, may not be done sufficiently well to meet the needs of the modeling community. Improvements to these measurements and an increased focus on their output are important to better constrain the atmosphere lower boundary. It also would be very helpful to develop a boundary layer VAP that consolidates surface and boundary layer properties. We need to add surface measurements and properties to the other sites, which could mean adding the equivalent of extended facilities to better spatially characterize surface preprocesses and properties that affect cloud formation. We don't have any current sites to provide ocean surface properties, but the AMF2 may be helpful in that regard.

Trade cumulus are an important potential target for ACRF observations

Trade wind cumuli cover a large portion of the Earth's oceans, particularly in sub-tropical regions. These clouds have been identified as particularly problematic in climate change scenarios. Relatively small changes in fractional coverage of these fair weather clouds have a large impact on the solar radiation reaching the surface, and therefore on ocean temperature. Consequently, these clouds are responsible for a large portion of the spread in climate model predictions of surface air temperature. It is possible to tweak the models to improve their performance in these regions, but it is not clear if these fixes actually get the physics right. Key measurements for addressing this problem include a radar (for cloud properties) and a

Raman lidar (for detailed measurements of water vapor over the diurnal cycle). The radar should be scanned at least in a plane (if not in 3D) to get a good measurement of spatial cloud cover at high temporal resolution.

It would be possible to measure marine boundary layer cumulus similar to the ones suggested here at the Manus site or during the upcoming AMF deployment to the Azores. However, these sites do have significant differences, in terms of temperature and humidity profiles, and possibly cloud characteristics, from the sub-tropical region where these clouds are most prominent. It would be preferable to go to approximately 20 degrees north or south. It would be ideal to locate a site in a subtropical region away from significant orographic effects. The orographic constraint would tend to rule out Hawaii. Possible solutions to the siting problem include deploying the AMF on a cargo container ship or on an oceanographic research vessel. Doing the experiment from a ship would also have the potential advantage of sampling different meteorological regimes within the subtropics (e.g., different sectors of a subtropical high pressure region).

Data products

A “data product” is a geophysical quantity that can be related to a model. ACRF collects data from many instruments. Sometimes these data are directly applicable to a range of applications and sometimes they require further work after collection. For example, currently it is difficult to get multiple parameters from different datastreams on a common time basis. The Cloud Modeling Best Estimate VAP includes hourly averages for some quantities and represents an important step in addressing that issue. Another issue is missing estimates of measurement uncertainties. It often isn’t enough to just have the value for a parameter, it is also important to have error bars.

Some VAP data products that were suggested in the discussion included a planetary boundary layer (PBL) product and a cloud retrieval (e.g., particle sizes and fall velocities) based on radar spectra. There was some discussion regarding whether it would be more useful for the infrastructure to do all VAP development or whether some of their effort should be spent developing tools and processes to facilitate development by the science user community. Involving the larger community in developing products has the potential of producing more VAPs, but there are also some risks to this approach. One problem is that there is the potential to have multiple versions of the same product. There would have to be sufficient documentation to distinguish among these versions. A second problem is that, with a new instrument, it is likely that some VAPs will be necessary to make the instrument useful, but relying on the user community to produce the necessary VAPs may take too long. The latter issue suggests that algorithm development has to be included in the cost of a new instrument.

There was a suggestion that the term “VAP” is too generic to cover the broad range of products that ACRF generates and that it might be more appropriate to go to a series of product “levels” that reflect the degree of data processing.

For existing VAPs, the modeling community is interested in long time series, where that is possible, versus a focus on field campaigns only. There also is an interest in obtaining data products for the mobile facility. It is not reasonable or even possible to generate all VAPs for all deployments; in some cases, the necessary input data may not be available. It may be possible to define a standard set of VAPs that are produced for all deployments, but the actual set needed for a given deployment varies. In part, it is the responsibility of the AMF site scientist to coordinate with the campaign principal investigator and the infrastructure to determine which VAPs should be produced.

Update from the Aircraft Vehicle Program Workshop

Rick Petty reported on the recent Aerial Vehicles Program (AVP) workshop, which provided a forum to discuss future airborne measurements. The results from the workshop will be presented in a separate report; however, a few highlights are given here. Some of the topics discussed were:

- Reducing uncertainties associated with small ice particle measurements
- Measuring net fluxes of shortwave and longwave radiation
- Fast time response of aerosol, cloud and state parameters
- Data processing techniques to reduce error bars
- Unmanned aerial systems
- Routine flights versus intensive field campaigns.

The small ice crystal problem is a significant constraint on our ability to make accurate retrievals and is also important for modeling. Pinning down the small ice crystal issue would be extremely valuable. The upcoming SPARTICUS experiment will be aimed, in part, at this issue. As a set of routine observations, this experiment will increase greatly the number of available hours. A typical field campaign may have ~30 hours out of which there are only ~5-10 good hours. In SPARTICUS, we are planning on 250 hours and hope to get >100 hours of good data, a large enhancement to the current database of ice cloud observations.

There is also a lot of interest in focusing on longer term flights to build up statistics. It is not clear how much data are needed for a given problem and whether the amount of time planned for SPARTICUS or RACORO is enough. However, if, after a period of time, the probability distribution function of particle properties stops changing, then we probably have enough data.